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THE ARL:UT SUBSEAFLOOR ENVIRONMENTAL SIMULATOR

Final Report under Contract N00014-77-C-0779

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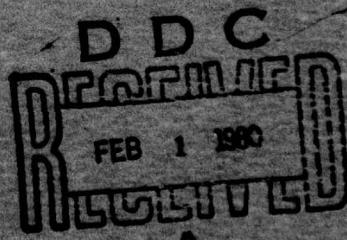
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An instrument has been constructed to simulate the natural environment of
the subseafloor so that acoustical and thermal measurements can be made
on a sediment at temperatures and pressures that duplicate in the laboratory
those found in the natural environment. Hydrostatic pressures to
5.2×10^8 dyn/cm^2 can be achieved by the instrument to simulate actual
sediment pore pressure. Frame or overburden pressure can be exerted on the
sediment up to 1.7×10^8 dyn/cm^2. Specimen temperature can be regulated

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from 0°C to 75°C. The instrument includes transducers and electronic equipment to make shear wave and compressional wave acoustic measurements as well as thermal conductivity measurements on the sediment at selected temperatures and pressures.

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LIST OF FIGURES

I. INTRODUCTION

Acoustical properties and their relationship to other physical properties of ocean sediments are important to the fields of underwater acoustics, physical oceanography, and geophysics. Basically there are two approaches to the measurement of sediment properties: in situ measurements in a real environment and laboratory measurements using a simulated environment. Although in situ measurements have the advantage that the environment is the natural one, there are the disadvantages that the measurements are difficult to make, the degree of disturbance is not easy to determine, and the environmental parameters are not subject to control so that one must make measurements in widely separated areas to obtain a range of parameter values. Moreover, due to limitations imposed by available measurement techniques, the in situ method can yield only limited quantities of data. Conversely, laboratory measurements can easily be made using a controlled environment to vary parameters and can yield large quantities of useful data provided proper attention is given to measurement techniques and equipment design.

The two dominant properties of the ocean bottom environment that must be simulated in laboratory measurements are temperature and pressure. The temperature of unconsolidated sediments in the bottom can range from near 0°C at the sediment-water interface to near 100°C at greater depths. There are two pressures encountered in natural sediments: frame, or overburden pressure due to the weight of the mineral grains, and pore fluid pressure resulting from the weight of the overlying water. Thus to obtain an accurate simulated environment for laboratory studies of sediments, the temperature, frame pressure, and pore pressure must be controlled over the range of values encountered in the ocean bottom.

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The purpose of this report is to describe an instrument which has been designed and built at Applied Research Laboratories, The University of Texas at Austin (ARL:UT), to enable the measurement of acoustical and other physical properties of real and artificial sediments at temperatures and pressures that simulate the real ocean environment. The system capabilities are as follows:

1. Achieve and hold a simulated sediment overburden pressure of 0 to 1.7×10^8 dyn/cm^2 (0 to 2500 psi).

2. Achieve and hold a pore fluid pressure of 0 to 5.2×10^8 dyn/cm^2 (0 to 7500 psi).

3. Maintain specimen temperature between 0° and 75°C.

4. Make acoustical measurements of compressional wave speed and attenuation and shear wave speed and attenuation at the above temperatures and pressures.

5. Make thermal conductivity measurements at the above temperatures and pressures.

The system consists of a stainless steel pressure chamber capable of withstanding the test pressures, with a hydraulically activated porous piston to exert the required frame pressure. An input port is included to allow the fluid pressure inside the chamber to be independently controlled. Acoustic and thermal transducers are rigidly mounted on the bottom of the chamber. The rest of the system consists of commercial and laboratory constructed electronic equipment mounted in an equipment rack for the acoustic and thermal measurements and the measurement of sample pressures and temperatures. A circulating thermal bath is used to control the temperature of the sample and container. Figure 1 shows the complete system.

In the following sections, the mechanical system consisting of the pressure chamber and associated hydraulic system will be described separately from the electronic system. In the electronic system, only the laboratory constructed equipment will be described in detail. Set-up and calibration of the system will be explained.

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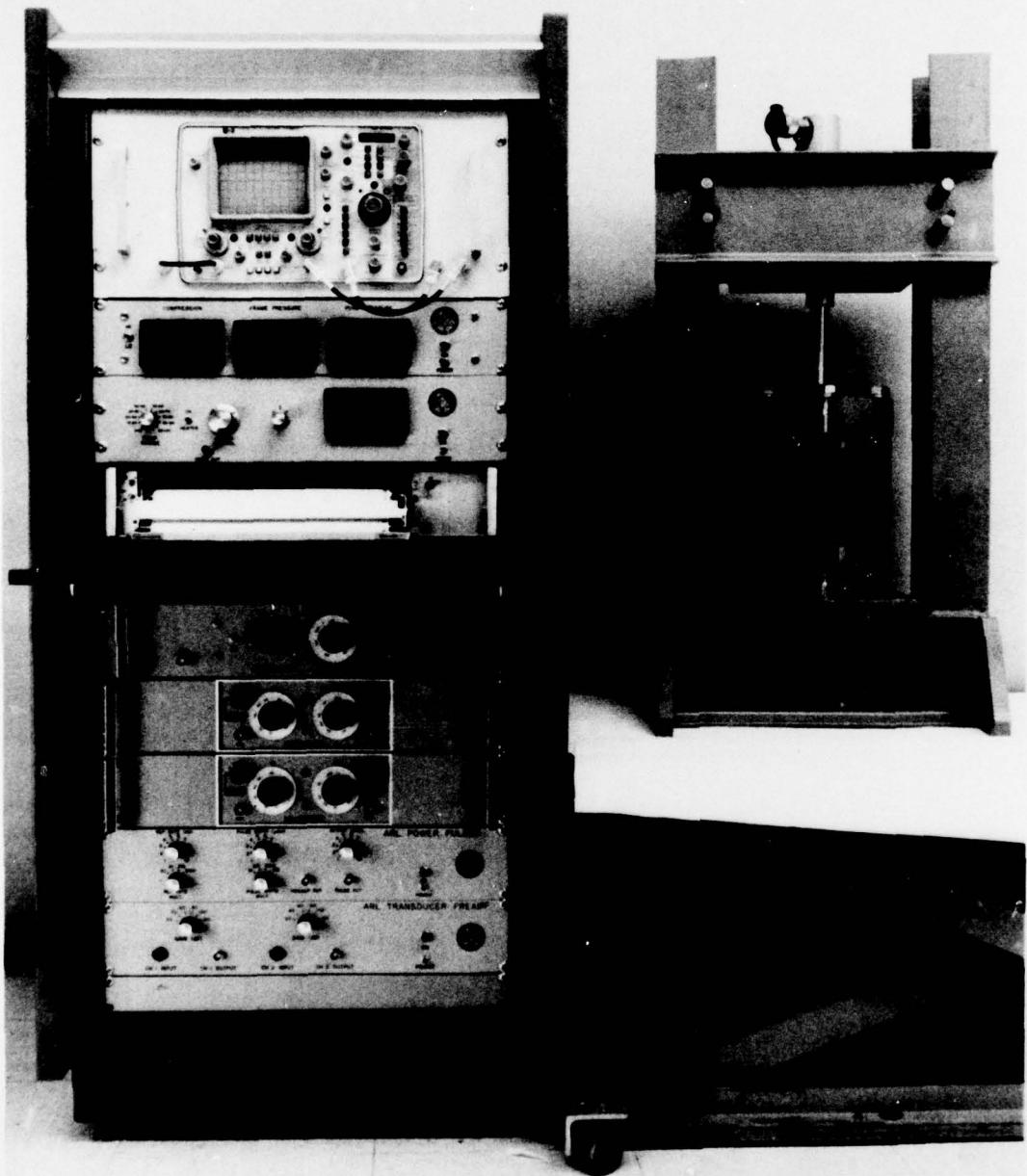
FIGURE 1
SUBSEAFLOOR ENVIRONMENTAL SIMULATOR SYSTEM

II. MECHANICAL SYSTEM

Figures 2 and 3 are photographs of the complete mechanical system of the environmental simulator assembled and disassembled. Various parts of the system are labeled in the figures. Figure 4 is a cross-section line drawing of the pressure chamber.

The stainless steel pressure chamber holds the sediment specimen; it has removable end caps. The top end cap contains a hole with O-ring seals to allow a piston to be moved inside the pressure chamber. The sediment is contained in a stainless steel sleeve (not shown in Fig. 3) which can be placed inside the pressure chamber. The sleeve has thin walls (2.4 mm) and a sharpened edge to allow a sample to be cut from a geophysical core and inserted into the pressure chamber. Dimensions of the sample tube are 55.2 mm i.d. x 156 mm high; the volume of sample contained in the sleeve is thus 373.3 cm^3. This quantity is important in calculating volume changes of the sample with overburden pressure applied. The piston is designed to be a close fit inside the sample sleeve; it also has O-ring seals so that none of the sediment can escape past the piston. The face of the piston is covered with a 6.4 mm thick porous stone with drainage holes through the piston behind the stone to allow free movement of the pore fluid into and out of the sediment during tests. Since the motion of the piston during a test must start above the surface of the sediment sample and since the O-rings on the piston would not enter the sample sleeve past the sharp cutting edge without some damage, a guide ring with the same thickness and diameter as the sample sleeve is placed above the sample sleeve and is machined in such a way that the guide ring fits over the cutting edge of the sleeve. Thus the piston starts out inside the guide ring and is smoothly guided into the sample sleeve as the sample is compressed. Total length of guide ring and sample sleeve is the same as the length of the pressure chamber.

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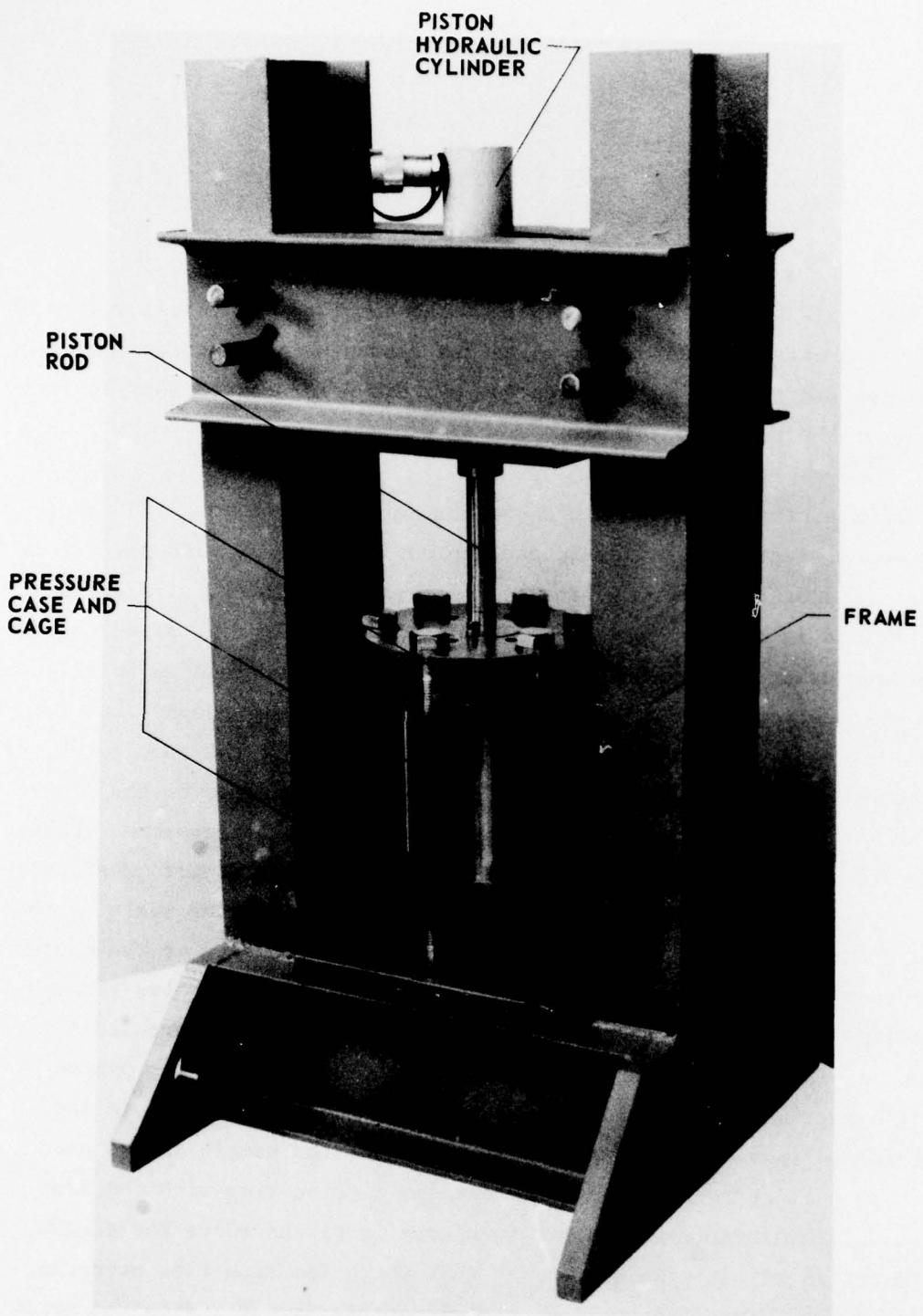
FIGURE 2
ASSEMBLED PRESSURE CASE AND HYDRAULIC PRESS
OF THE ENVIRONMENTAL SIMULATOR

3447-7

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FRAME

CAGE FOR
PRESSURE
CASE

TOP END
CAP

PRESSURE
CHAMBER

HYDRAULIC
CYLINDER
FOR PISTON

PISTON
AND ROD

POROUS
STONE
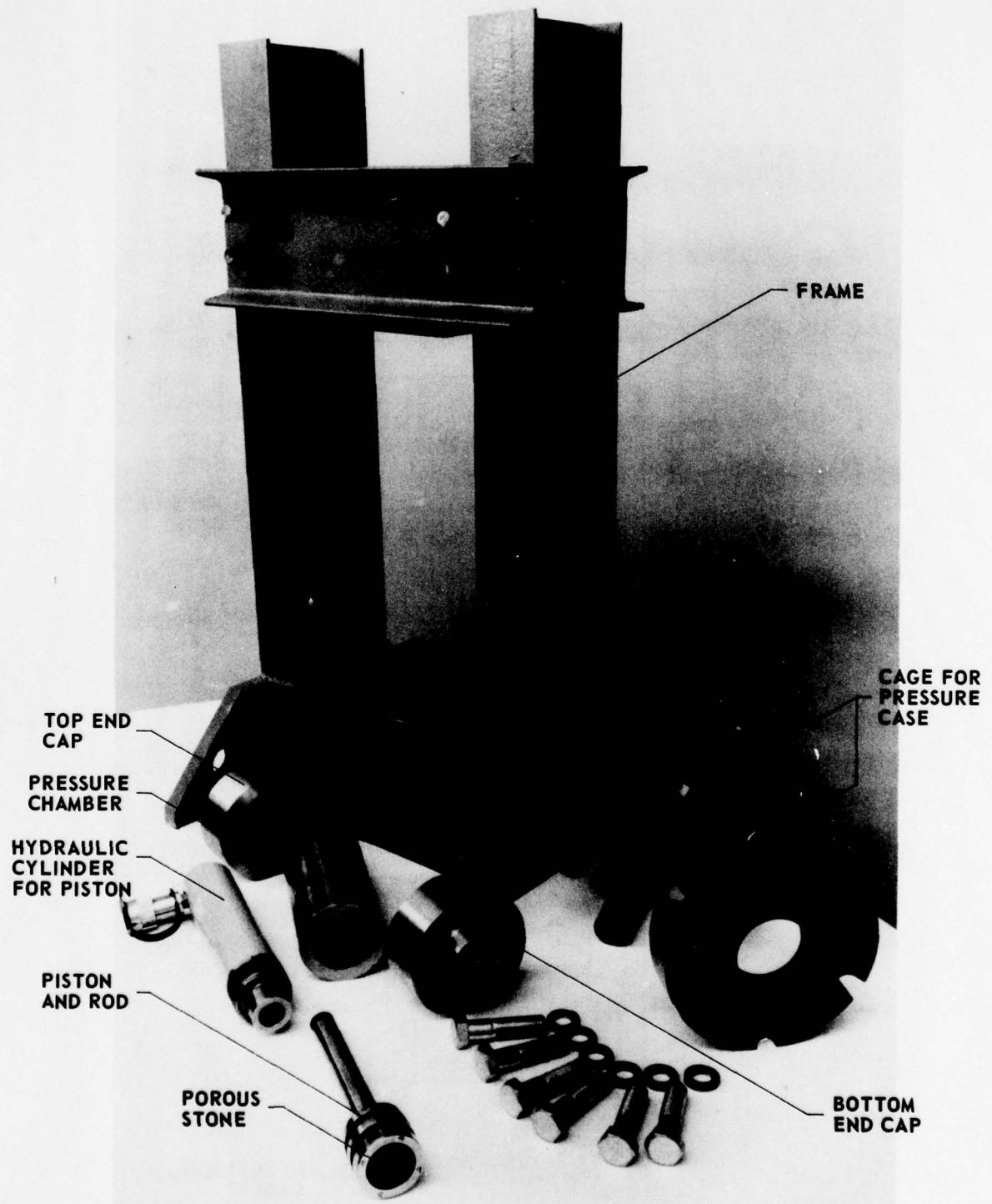
BOTTOM
END CAP

FIGURE 3
ENVIRONMENTAL SIMULATOR DISASSEMBLED

3447 - 3

PISTON ROD

OUTLET PORT

INLET PORT

TOP CAP

FLUID VENT

O-RING SEALS

GUIDE RING

PRESSURE CASE

POROUS STONE

SEDIMENT SAMPLE

SAMPLE SLEEVE

THERMAL TRANSDUCER

ACOUSTIC TRANSDUCER

ACOUSTIC TRANSDUCER

BOTTOM CAP

ELECTRICAL CABLES
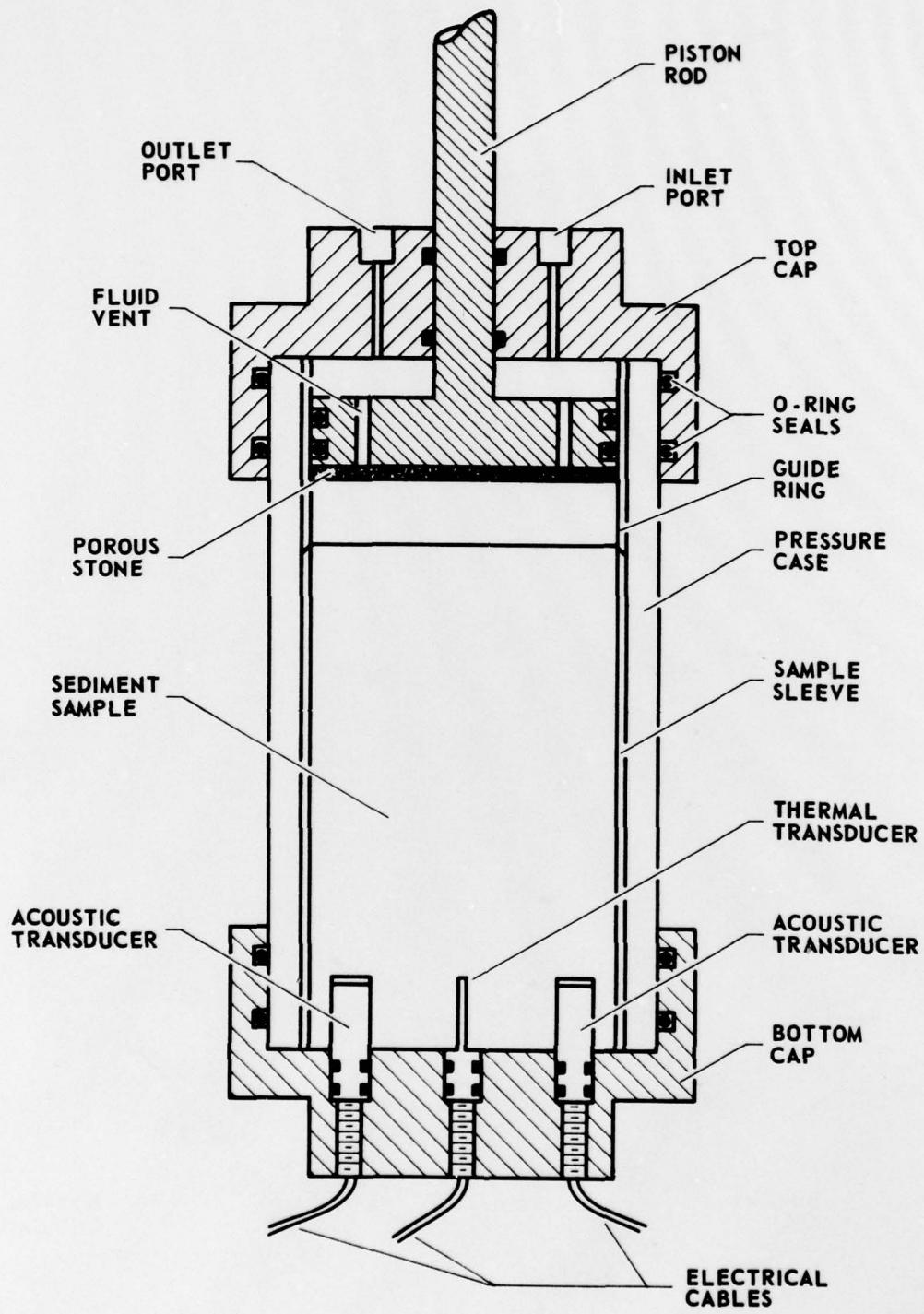
FIGURE 4
PRESSURE CHAMBER CROSS-SECTION

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The bottom end cap of the pressure chamber contains the mounting holes for the acoustic and thermal transducers. Each hole consists of a bottom threaded portion to accept the threaded bases of the transducer mounts and a smooth portion at the top for the O-ring seals on each transducer base. There are three acoustic transducers--one projector and two receivers, and one thermal conductivity transducer. The holes for the three acoustic transducers are arranged such that the two receiver transducers are at different distances from the projector. The thermal probe mounts in the center hole. Blank plugs are supplied so that the system can be used without the transducers.

Figure 5 is a schematic representation of the acoustic transducers designed to be mounted in the environmental simulator chamber. The transducers have both shear wave and compressional wave elements. The shear wave element is a bender 6.35 mm long x 1.59 mm wide and 0.5 mm thick. The bender type element has been used before for generation and detection of shear waves in highly unconsolidated sediments.[1,2] The compressional wave element is a lead zirconate titanate ceramic with dimensions of 3.18 mm x 3.18 mm x 0.79 mm polarized and driven in the thinnest dimension. The elements are mounted on a 25.4 mm x 12.7 mm x 0.79 mm stainless steel blade with appropriate cutouts to receive the transducer elements. The shear wave element is bonded to the metal holder at the back end of the element. The compressional wave element is isolated from the metal holder but held rigidly in place by a polyurethane potting compound which covers the whole area of the blade. The blade is rigidly mounted along its bottom edge to the threaded holder. Small insulated wires are bonded in the plastic coating to connect the active elements to a 4-conductor shielded cable which runs through the bottom of the holder and connects to the electronic system. Projector and receiver transducers are identical and can be interchanged. Utilization of the above design enables the transducers to be easily replaced in case of failure or damage.

The thermal transducer is similar in design to that developed by Von Herzen and Maxwell in 1959.[3] A small thermistor bead is mounted midway inside a 6.35 cm long stainless steel #20 hypodermic needle with a

1.6 mm x 6.3 mm
BENDER SHEAR WAVE
TRANSDUCER ELEMENT

3.2 mm x 3.2 mm x 0.79 mm
COMPRESSIONAL WAVE
TRANSDUCER ELEMENT

METAL
BLADE

O-RING
SEALS

1/2-13
THREADS

4-CONDUCTOR
SHIELDED CABLE
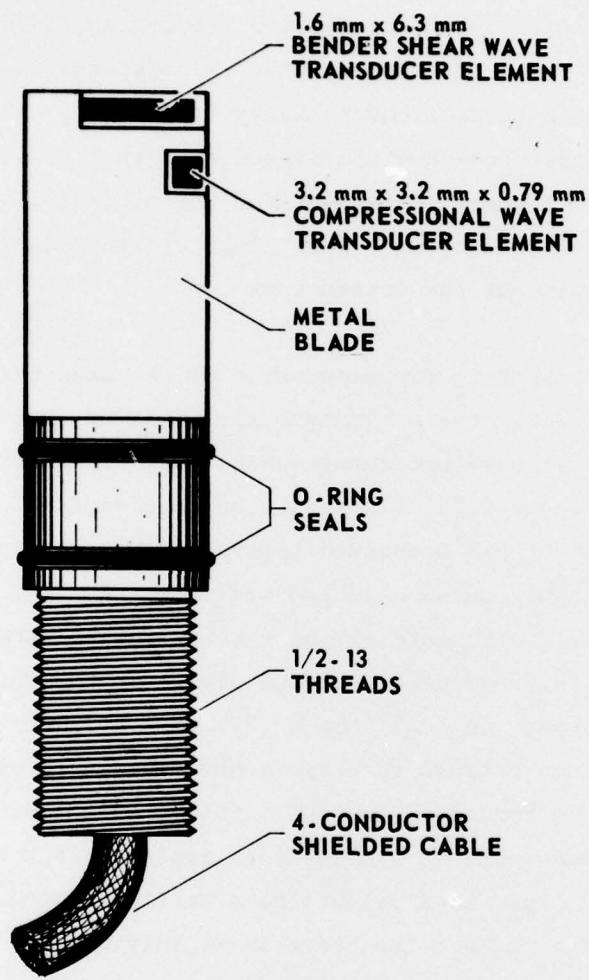
FIGURE 5
ACOUSTIC TRANSDUCER

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fine heater wire loop which runs the length of the needle. The probe is
mounted on a base identical to those used for the acoustical transducers.
Again, a 4-conductor cable connects the heater wire and thermistor to the
electronic measuring system. The thermistor can be used by itself to
monitor the temperature of the sample at a point very near the path of
acoustical propagation. The heater and thermistor can be used together
to measure thermal conductivity of the sample.

Since the pressure inside the chamber would tend to force the end-caps
off the chamber, a heavy steel cage is used to hold the pressure chamber
together. The cage is shown in Figs. 2 and 3. The pressure chamber-cage
combination is designed to be mounted in a heavy steel frame so that a
force can be exerted on the piston rod which projects from the top of the
pressure chamber. The bottom plate of the frame has appropriate clearance
holes for the bolt heads of the cage and also holes through which the
electrical cables from the transducers can be placed. The bottom plate is
constructed of 19 mm (3/4 in.) thick armor plate steel for maximum stength.
The top cross-member of the frame holds the hydraulic cylinder which is
used to exert force on the piston. This cross-member is held in place by
4 steel pins and is easily removable so that the pressure chamber and cage
can be placed in the frame.

For temperature control of the specimen, a coil of 9.5 mm (3/8 in.)
o.d. copper tubing is wrapped around the stainless steel pressure cylinder
and is bonded to it by thermally conductive epoxy. This coil is not shown
in the figures. To thermally isolate the pressure chamber from the frame
when operating far from room temperature, a 6.35 mm (1/4 in.) thick
asbestos plate is supplied which has the same dimensions and hole pattern
as the bottom plate of the frame.

One of the physical properties of a sediment that is of interest for
comparison to the acoustical properties is the porosity of the sediment.
To enable calculation of the change in porosity experienced by the sediment
in response to changes in overburden pressure, the system incorporates a
device to accurately measure the amount of piston displacement. The

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measurement device consists of a linear variable differential transformer
capable of measuring ±7.62 cm (±3 in.) mounted on the frame parallel to
the piston hydraulic cylinder. The armature of the transformer is con-
nected by a clamp to the piston rod. A digital display in the equipment
rack shows the displacement in two switch selectable ranges. In the low
range, the meter will read ±1.9999 in. while in the high range the meter
will read ±19.999 in. in case of large piston displacements. The linear
range of the LVDT is ±7.62 cm (±3 in.).

The hydraulic system of the simulator consists of two Enerpac hand
pumps and two Enerpac 10-ton cylinders. The system is shown in schematic
form in Fig. 6. The cylinder that supplies frame pressure to the sample
drives the piston and rod directly. The other cylinder is mounted on a
small stainless steel cylinder with a piston to supply the pore fluid
pressure to the system. Electronic pressure sensors monitor and display
hydraulic fluid pressure of the frame pressure system and the pore fluid
pressure of the other system over the range of 0-10,000 psi.

STAINLESS
NIPPLE
1/4 NPT × 1/4 NPT

ENERPAC
CYLINDER
10-TON

ELECTRONIC
PRESSURE
SENSOR
0-10,000 psi

QUICK
DISCONNECT
COUPLING
3/8 NPT IN
AND OUT

MANIFOLD
3/8 NPT INPUT
3/8 NPT MALE OUTPUT
1/4 NPT FEMALE OUTPUT

QUICK
DISCONNECT
COUPLING
3/8 NPT IN
AND OUT

6 ft FLEX HOSE
10,000 psi
MAXIMUM

6 ft FLEX HOSE
10,000 psi
MAXIMUM

3/8 NPT MALE
FITTING ON
HOSE

ENERPAC PUMP
10,000 psi MAXIMUM
MODEL P-39

ENERPAC PUMP
10,000 psi
MAXIMUM
MODEL P-39

3/8 NPT
MALE
FITTING
ON HOSE

FIGURE 6
SUBSEAFLOOR ENVIRONMENTAL SIMULATOR
HYDRAULIC SYSTEM

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III. ELECTRONIC SYSTEM

The electronic system of the simulator incorporates all of the
measurement electronics in one complete unit; no other equipment is
required to make measurements. Figure 7 is a block diagram of the system.
There are three subsystems in the unit, one to make acoustical measure-
ments, another to make thermal measurements, and another to measure and
display pore pressure, frame pressure, and piston displacement.

A.   Acoustic Subsystem

The acoustical measurement subsystem consists of a power pulse
generator to drive the projector, a dual preamplifier for the receiving
transducers, two variable bandpass filters for the received signals, and
an oscilloscope to monitor the signals and measure the time difference
between the received pulses.

The power pulser drives the projecting transducer with a square pulse
of variable amplitude, duration, and repetition rate. The amplitude is
variable from 0 to 40 V into a load of 20 to 2000 Ω. Pulse duration can
be varied from 1 μsec to 10 msec. Repetition rate can be adjusted from
1 pulse every 10 sec to 1000 pulses/sec. Provision is made to supply a
trigger signal to the oscilloscope at the beginning of each transmit pulse.

The preamplifier unit is dual channel and consists of a rack mounted
assembly plus small individual units cabled to the rack unit and mounted
on the frame of the pressure chamber to be near the receiver transducers.
This design allows the high impedance cable between transducer and
preamplifier to be short to minimize noise pick-up. The cable connections
between the preamplifier boxes and the main unit are low impedance

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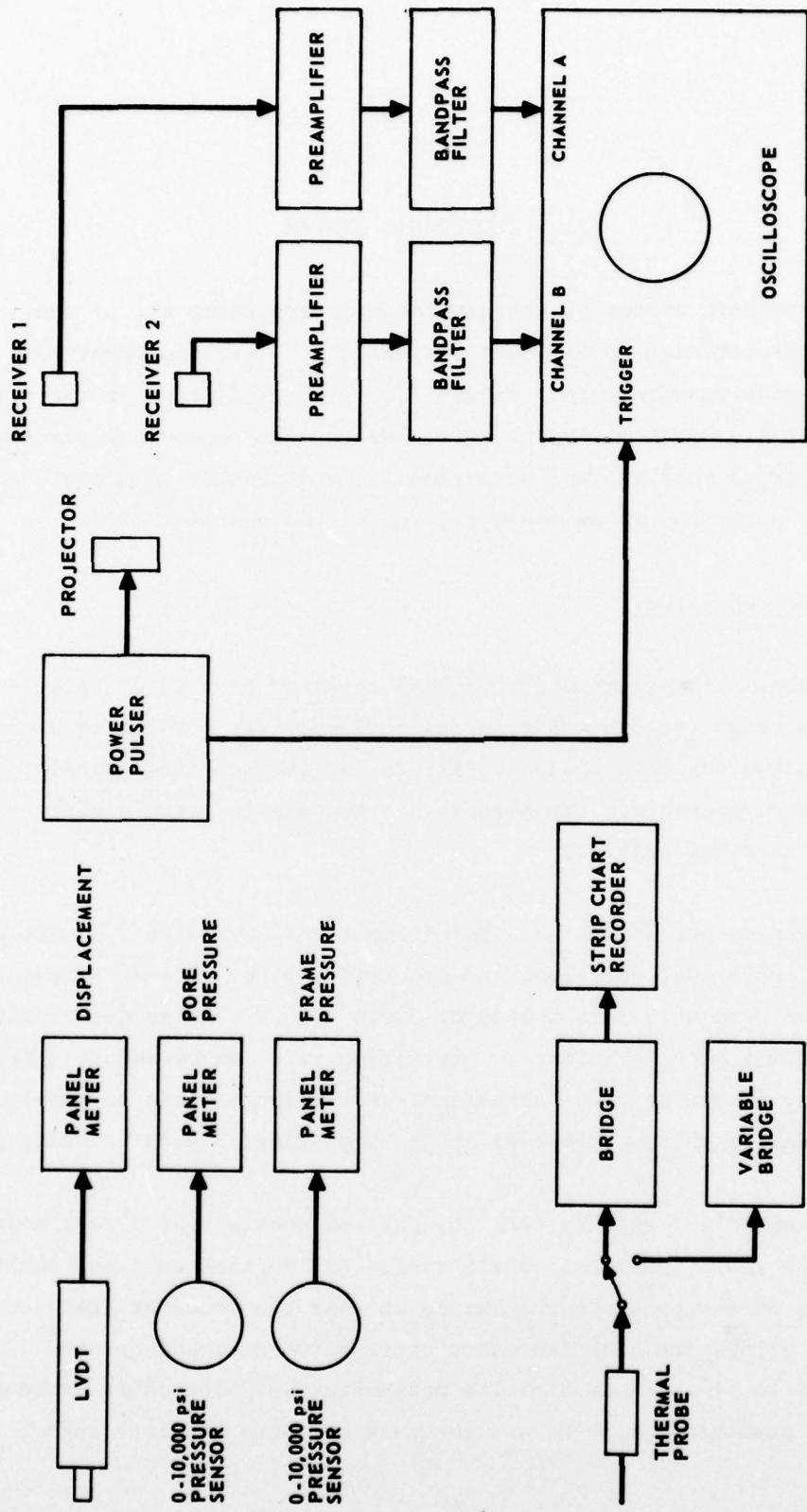
FIGURE 7
SUBSEAFLOOR ENVIRONMENTAL SIMULATOR
BLOCK DIAGRAM

allowing long cables with minimum noise pick-up and signal degradation. In this way, the equipment rack and pressure chamber can be separated by several tens of meters without signal degradation from long cable runs.

The power pulser and the preamplifier were both designed and constructed at ARL:UT. A detailed circuit description is presented in Section IV.

The output of each channel of the preamplifier is bandpass filtered by a Krohn-Hite model 3100R solid state variable filter. High and low cutoff frequencies can be independently varied from 10 Hz to 1 MHz. The passband gain is unity (0 dB) and the roll-off is 24 dB per octave outside the passband. The operation and maintenance of the filters is described in detail in the manual supplied with the units.

The amplified and filtered signals are applied to the inputs of a Hewlett-Packard Model 1743A oscilloscope. The oscilloscope is 2-channel with provision for measuring the time difference between two adjustable points on one trace or between one point on one trace and another point on the other trace. The time measurements are accurate to ±2% at sweep speeds from 50 nsec/div to 20 msec/div and at ambient temperatures of +15°C to +35°C. One operating mode of the oscilloscope allows the pulse on one trace to be superimposed on the pulse of the other trace and their time differential (Δt) measured and displayed digitally. The method of Δt measurement by cycle to cycle matching in overlapped pulses is recognized as the most accurate way of sound speed measurement using pulse techniques.[4]

B.   Thermal Subsystem

The thermal measuring subsystem consists of the thermal probe, the two measuring bridges and a Leeds and Northrup strip chart recorder. Both of the bridges are laboratory constructed and will be discussed in detail later. One is a variable Wheatstone bridge with calibrated controls in decade resistance ranges with an output for a voltmeter to

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indicate when the bridge is balanced. This bridge is for accurate
calibration of the thermal probe and measurements when only the temperature
of the sample is required. The second bridge is used with the strip chart
recorder to measure thermal conductivity. The thermal conductivity bridge
includes a digital panel meter which allows measurement of the voltage
across and the current through the resistance heater element in the thermal
probe. The panel meter also is switch selectable to read temperature.
The output of the bridge is recorded as a function of time by the strip
chart recorder. Thermal conductivity is measured by recording the change
in temperature of the thermal probe imbedded in the sample after a known
amount of electrical power is supplied to the heater in the probe.

C.   Pressure and Displacement Subsystem

The pressure and displacement subsystem consists of a rack unit to
supply power to the two pressure gauges and the differential transformer,
each of which has all necessary electronic circuits included in the gauge.
The rack unit has three digital panel meters for displaying pressures and
displacement. This unit was also constructed at ARL:UT and will be
discussed in detail later.

IV. ELECTRONIC CIRCUIT DESCRIPTIONS

A. Power Pulser

Figure 8 is a schematic of the power pulser unit of the simulator.
The circuit incorporates two NE555 integrated circuit timers to provide
square pulses at selected repetition rates and pulse widths to a
5-transistor power driver. The driver stage used power field effect
transistors to drive the transducer. They were selected because of
their lack of secondary breakdown, their thermal stability, and their
near indestructibility when properly protected.

IC1 and associated components form an astable multivibrator. The
ON time of the output at pin 3 of IC1 is controlled by the sum of R1, R2,
and R3 and the capacitance selected by the REPETITION RATE MULTIPLIER
control S1. The OFF time of the output is controlled by R3 and the
selected capacitor. By properly setting S1 and R1 the ON time can be
varied from 1 msec to 10 sec thus giving a repetition rate from 1000 pps
to 0.1 pps. The output at pin 3 of IC1 is coupled to the monostable
multivibrator circuit formed by IC2 and associated components. C7 and
R4 form a differentiating network to shorten the pulse applied to the
trigger input, pin 2 of IC2. Each time pin 2 of IC2 is pulled toward
ground by the pulse from IC1, the output of IC2, pin 3, goes to +5 V and
remains there for a time interval determined by R5, R6, and the capacitor
selected by the PULSE WIDTH MULTIPLIER control S2. By properly setting
R5 and S2 the pulse width can be varied from 1 µsec to 10 msec. The
pulse at the output of IC2 is supplied to the TRIGGER OUT connectors on
the front and rear panels of the unit and also drives the power driver
circuits. Q1 inverts the pulse from IC2. The inverted pulse drives Q2,
which inverts the pulse again and transforms the +5 V level up to +36 V
level. The high level pulse drives emitter follower Q3 which has the

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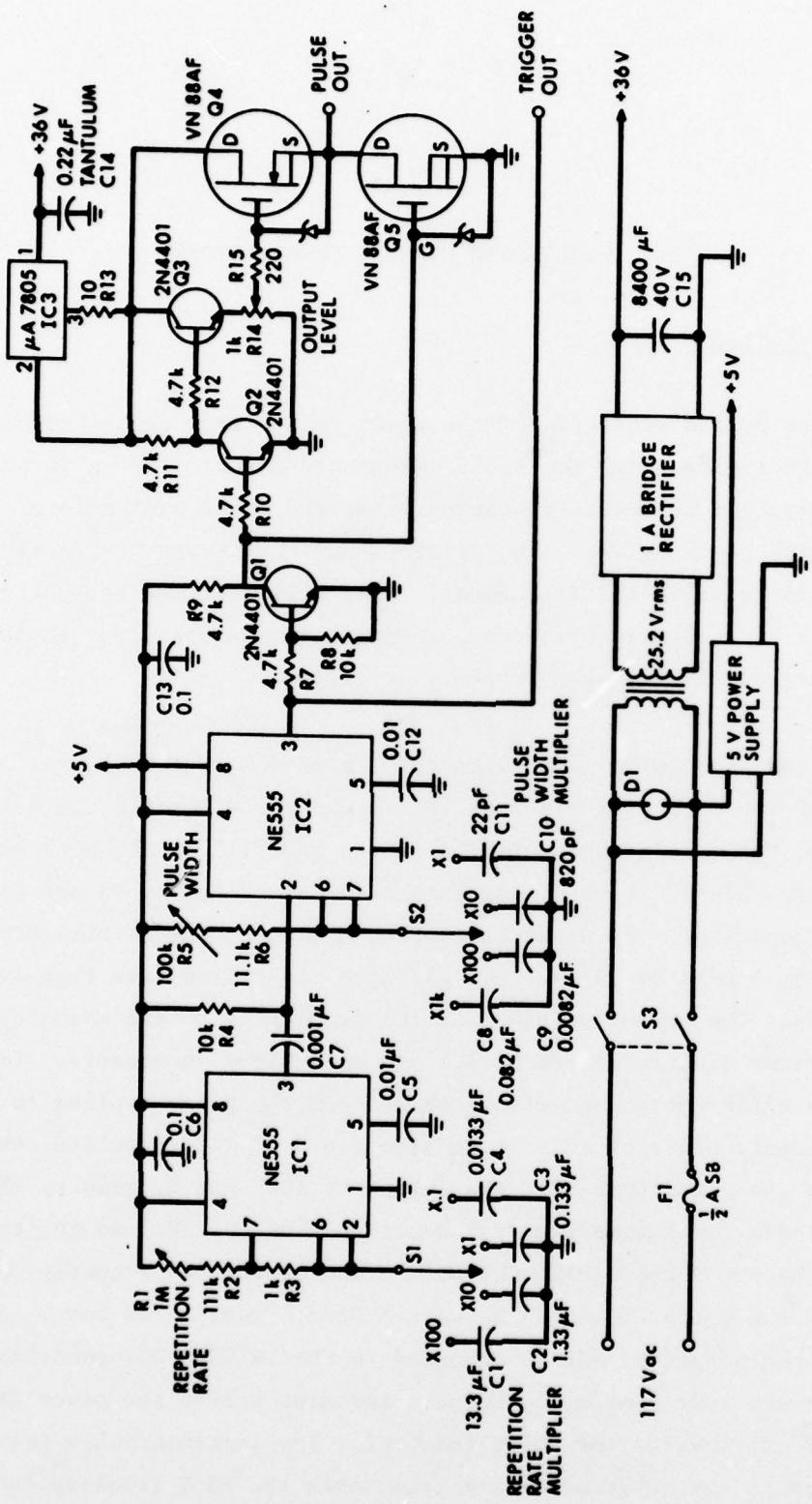
FIGURE 8
POWER PULSER SCHEMATIC DIAGRAM

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OUTPUT LEVEL control R14 as emitter resistor. A variable level pulse is tapped off by the slider of R14 to drive Q4, which is a power FET wired as a source follower to drive the load applied to the PULSE OUT connector on the front panel. Q5 is driven 180° out of phase with Q4 and acts to clamp the output line to ground during the periods between pulses. Clamping the output reduces ringing of the transducer and shortens the acoustic pulse that is generated. IC3 and R13 form a current limiter for the output stage. The power FET is capable of carrying 2 A of current. However, the current supply to the final stage is limited to 0.5 A so that the output transistor is protected if the output is shorted to ground.

B.   Preamplifier

Figure 9 is a schematic of one channel of the preamplifier. Both channels are identical and the unit incorporates a single power supply for both channels.

Each preamplifier circuit is in two sections, one housed in a small aluminum box to be placed near the transducer, the other, in the rack panel. Four-conductor shielded cable connects the transducers to the preamplifier box through P1 and SC1, and also connects each box to the rack unit.

IC4 and IC5 form a differential input/differential output amplifier with 20 dB gain; R19, R20, and R21 set the gain. R16 limits the input impedance to 10 MΩ. S4 selects either the shear wave or compressional wave transducer, shorting the unused transducer to ground to eliminate feedover interference.

IC6 forms a variable gain differential input/single output stage. IC7 is a single input/single output stage with variable gain. The gain-setting resistors selected by switch S5 vary the gain of the final two stages from 0 to 100 dB in 20 dB steps. Since the first stage has a constant gain of 20 dB, the total gain of the complete circuit can be

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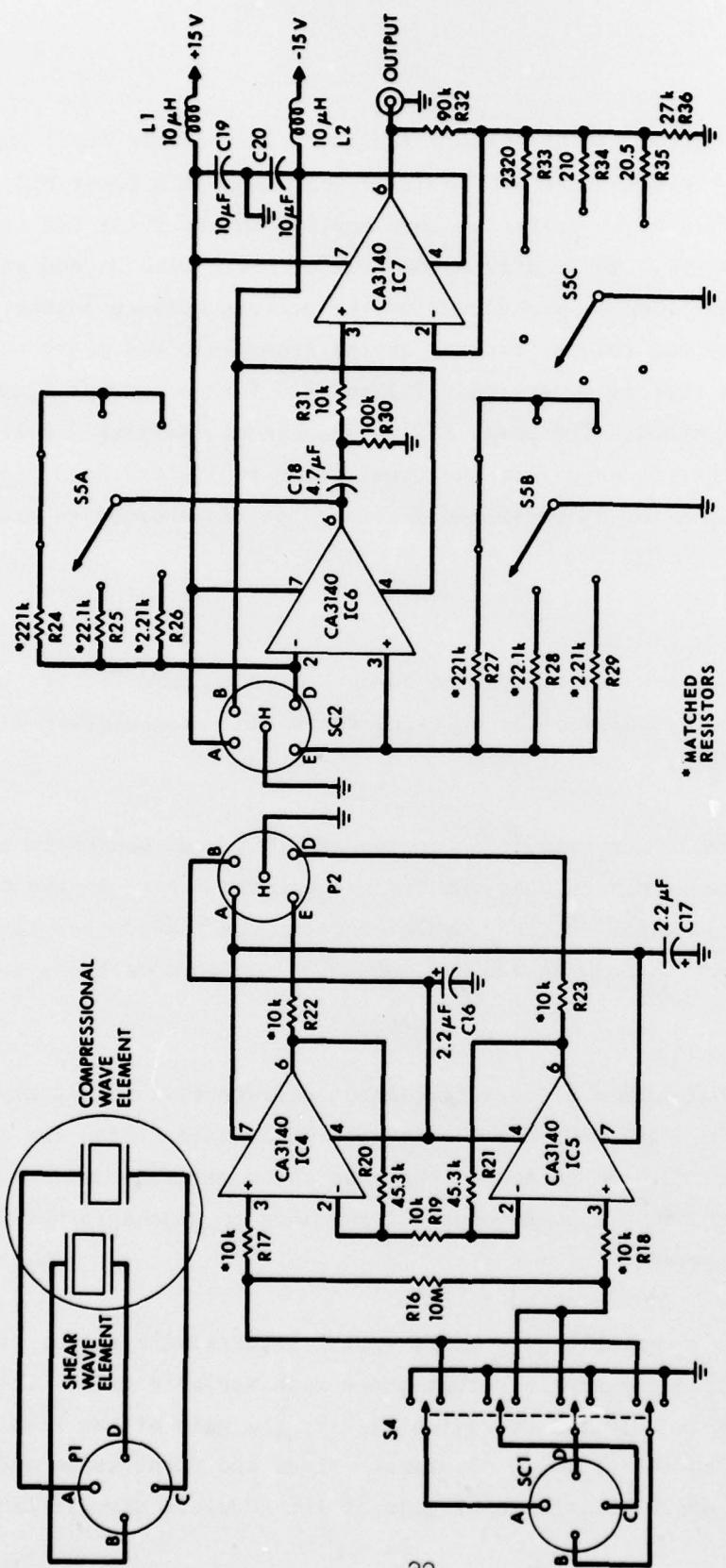
FIGURE 9

PREAMPLIFIER SCHEMATIC DIAGRAM

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varied from 20 dB to 120 dB. C18 and R30 form an ac coupling circuit so that dc offset at high gain settings does not saturate the final stages.

C. Thermistor Bridge

Figure 10 is a schematic of the thermistor bridge. The circuit is a standard Wheatstone bridge with 4 decade resistor switches. A socket on the front panel accepts the plug on the cable from the thermal conductivity probe. Switch S6 connects the battery supply to the circuit. The bridge is connected to two phone tip jacks on the front panel. The output can be monitored at these jacks by a voltmeter to detect the point at which the bridge is balanced by the switchable decade resistors; the bridge is balanced when the output is zero. The thermistor resistance is then read off the decade switch knobs on the front panel of the unit.

D. Thermal Conductivity Bridge

The thermal conductivity measuring unit is used with the thermal conductivity probe which is mounted in the pressure case to measure the thermal conductivity of a sediment sample at various pressures and temperatures. Figure 11 shows a block diagram of the electronic unit. SC3 is the input socket on the rear panel of the unit for the thermal probe plug. Pins A and B on the plug connect to the heater in the probe; pins C and D connect to the thermistor. Switch S7 selects the data displayed on the digital panel meter. In the E position the meter displays the voltage across the probe heater element and in the I position displays the current through the heater. In the T position the meter displays the temperature that is measured by the probe thermistor and thermistor bridge. The panel meter has an input range of 0 to 1.999 V. R43, R44, R45, and R46 form a divide-by-ten network to reduce the heater voltage (0-12 V) to the range of the meter. Current through the heater is measured by detecting the voltage across R47, which is a 10 Ω resistor in series with the heater. The differential amplifier following S7A and S7B is an X1 gain amplifier required to remove the voltage offset due to R47 from the heater voltage reading. S7D selects the proper

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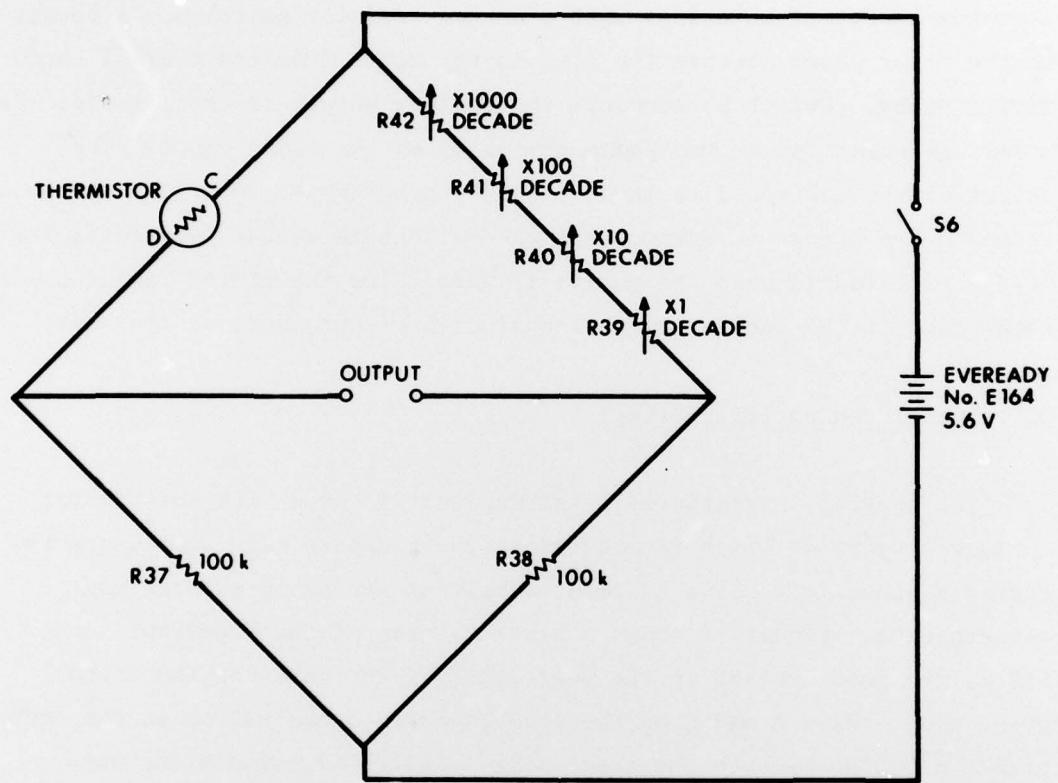
FIGURE 10
THERMISTOR BRIDGE SCHEMATIC DIAGRAM

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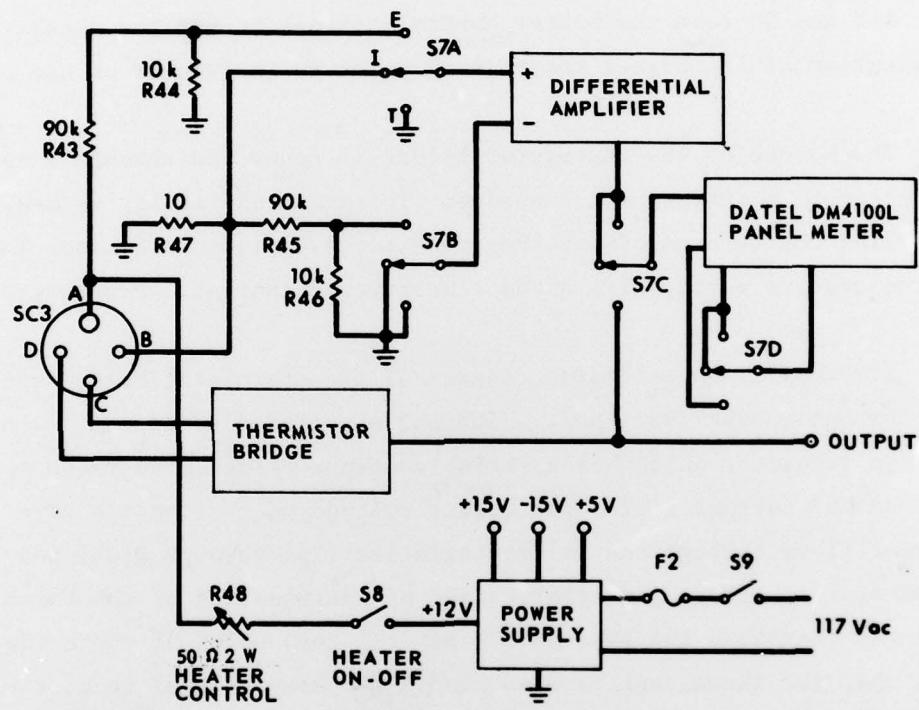
FIGURE 11
THERMAL CONDUCTIVITY BRIDGE BLOCK DIAGRAM

position of the decimal point on the meter display. In the temperature mode the meter displays a range of 19.999°C while a range switch in the thermistor bridge circuit selects 10°C ranges from 0° to 100°C. Thus the actual temperature is the sum of the range switch reading and the meter reading. For example, if the range switch is set to 10° and the meter reads 5.000, then the temperature is 15.000°C.

R48 and S8 form the heater control circuit to set the power dissipation of the heater and to turn power to the heater on and off.

The output of the thermistor bridge is connected through a rear panel connector to a strip chart recorder. Thermal conductivity is measured by recording the temperature of the probe for a period of 10 min. The slope of temperature versus time gives a measure of thermal conductivity.[3]

Figure 12 is a schematic diagram of the thermistor bridge section of the thermal conductivity unit. IC8 and associated components form a low voltage regulator which has a variable output selected by range switch S10. R52 and R53 further divide the output voltage so that only a very small current flows through the bridge resistors (R64 through R103) and the thermistor to reduce the error caused by self-heating of the thermistor. Variable resistors R64 through R73 set the zero point of the bridge so that when the thermistor is measuring a temperature that is at the midpoint of a temperature range, the output of IC9 can be set at 0 V. Calibration resistors R54 through R63 control the span of the bridge so that when the thermistor is measuring a temperature at the bottom end of a range, the output of IC9 can be set to -5.000 V. Each range of the bridge has a set of calibration controls. IC10 provides a variable offset to the output of IC9 so that when measuring a temperature at the bottom of a range, the output from IC10 is 0 V and at the top end it is +10.000 V. The offset is controlled by R114.

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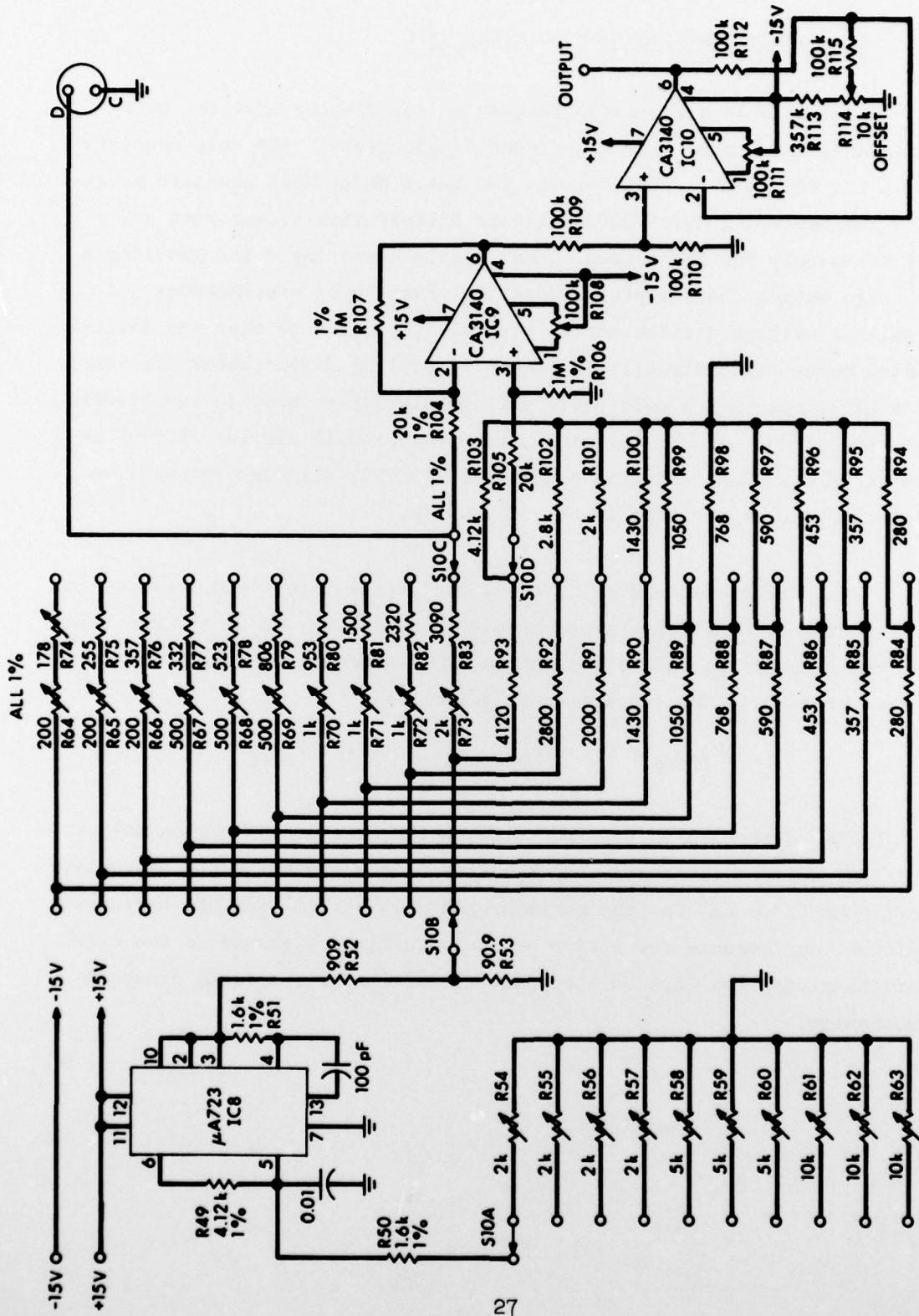
FIGURE 12

THERMISTOR BRIDGE SCHEMATIC DIAGRAM

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E. Pressure and Displacement Display Unit

Figure 13 is a schematic diagram of the display unit for pore pressure, frame pressure, and piston displacement. The unit consists of a +24 Vdc power supply for the two Setra Model 204E pressure gauges and the Schaevitz Model 3000HR linear differential transformer and a +5 Vdc supply for the meters. Each of the measuring units provides a voltage output that is proportional to pressure or displacement. A resistor voltage divider scales the voltage output so that the digital panel meter reads directly in pressure (psi) or displacement (inches). The LVDT input has a switchable voltage divider to provide two levels of resolution. In the low range, the readout will display ±1.9999 in., while in the high range the display is ±19.999, although the maximum linear range of the LVDT is only ±3.000 in.

The pore pressure display reads the actual pore fluid pressure in the sediment. The frame pressure display, however, reads the hydraulic system pressure so that a correction must be made to obtain the actual frame pressure. The correction is given by:

$$P_{frame} = 0.610 \ P_{hydraulic} - 0.188 \ P_{pore} \quad . \tag{1}$$

The correction is required because the area of the piston acting on the sediment is larger than the area of the piston in the hydraulic cylinder (23.6 cm^2 for the sediment piston, 14.4 cm^2 for the hydraulic piston) and because the action of the pore fluid pressure on the area of the piston rod (4.4 cm^2) opposes the action of the frame pressure mechanism.

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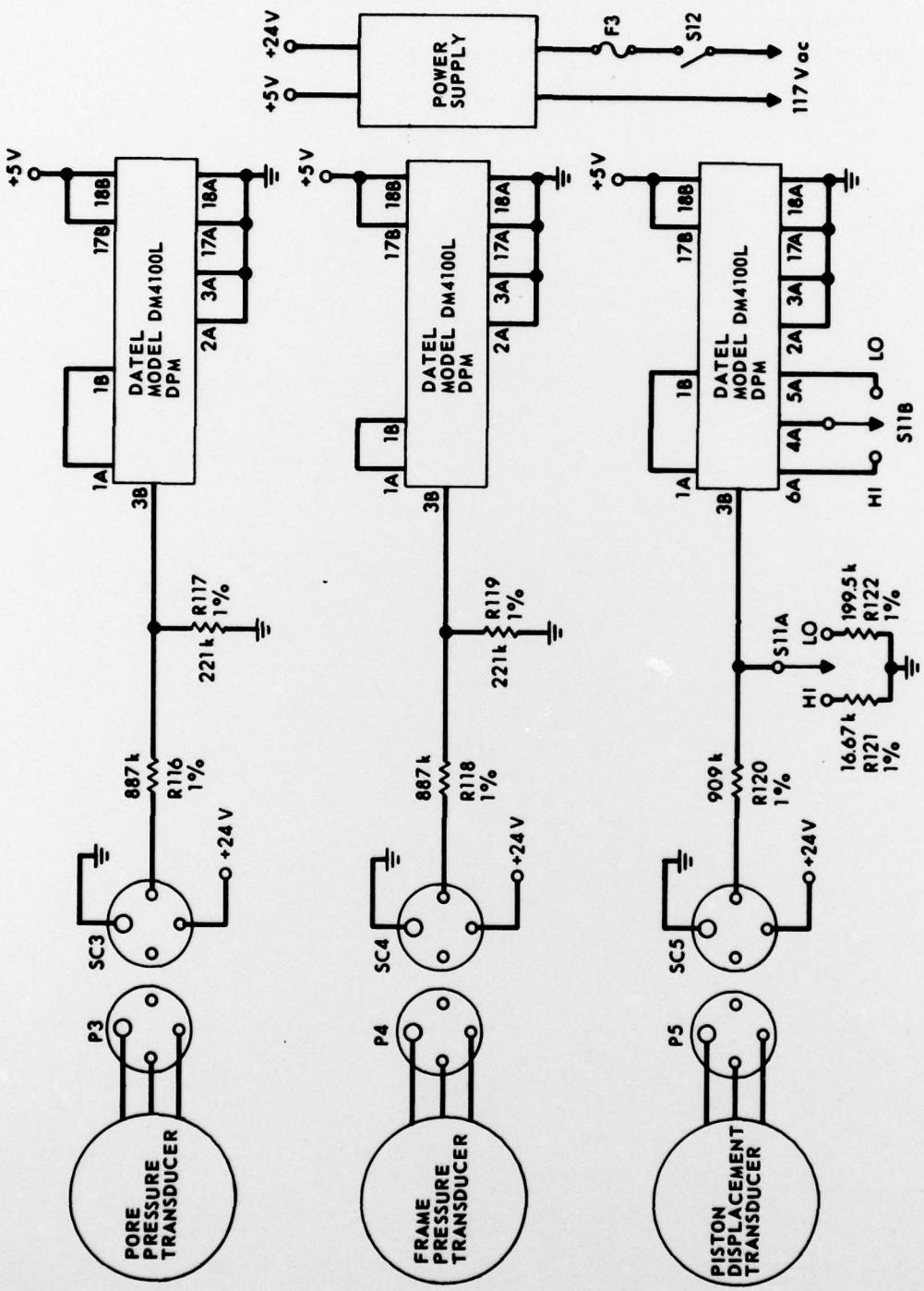
FIGURE 13

PRESSURE AND DISPLACEMENT DISPLAY UNIT
SCHEMATIC DIAGRAM

V. CALIBRATION

Calibration procedures for the commercial electronic units in the simulator system are described in detail in the technical manuals supplied with the equipments. The only calibrations that can easily be carried out on the rest of the system are the determination of acoustic transducer spacing and sensitivity and the calibration of the thermal conductivity measuring unit.

Determination of transducer spacing is done with distilled water in the sample chamber. Since the compressional wave speed of sound in distilled water over a large temperature range is accurately known and listed in a number of handbooks, the separation between the two receivers can be calculated by measuring the time differential between the two received pulses and the temperature of the water in the chamber. The separation, D, is calculated as follows:

$$D = \Delta t \ c \quad , \tag{2}$$

where c is the speed of sound in water at the measured temperature and Δt is the difference in time between reception of the pulses at the two receivers. Since the shear wave and compressional wave elements are rigidly bonded together in the transducer, the same spacing determined for the compressional wave elements can be assumed for the shear wave elements.

Sensitivity of the compressional wave elements can be determined with relative ease because distilled water has such a low attenuation factor that it can be assumed to be zero. Thus the difference in amplitude between the received pulses from the compressional wave elements is due to spreading loss and differences in sensitivity, both of which should remain constant as long as the transducers are not disturbed. Thus, any

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changes in amplitude of the received signals can be interpreted as attenuation when another medium replaces the water. The measurements are complicated, however, by the fact that the sensitivity of each element is a function of ambient temperature and does not necessarily track the response of the other element. So, if attenuation measurements are to be made as a function of temperature, the water calibration must be made over the same temperature range.

Due to the lack of a medium for shear wave propagation with consistent properties and that can readily be placed in the test chamber, an accurate attenuation calibration of the shear wave transducers cannot easily be made. However, a dry sand such as Ottawa sand will generally come to the same state of compaction each time it is placed in the container if it is allowed to fall, a small amount at a time, from a height of at least 1 m. The shear wave speed and attenuation for such a sample is thus repeatable to a degree. A rough calibration of the shear wave transducers can then be made by measuring the received pulse amplitudes with the receiver transducers in one configuration and then with their positions switched. The difference in amplitudes of the signals from each transducer when in the near and far positions should match that of the other transducer and is the signal loss due to spreading and attenuation. Thus the actual sensitivity of each transducer can be calculated.

For calibration of the thermistor in the thermal conductivity probe, an accurate temperature measuring device such as a quartz thermometer or platinum resistance thermometer is necessary. The temperature measuring device and the probe can be placed together in the Lauda circulating bath so that temperature can be varied. With the probe connected to the variable bridge unit, the resistance of the thermistor is determined at closely spaced intervals over the temperature range 0°C to 75°C. The data are plotted and a curve of resistance versus temperature determined for the thermistor. Once the resistance curve has been found, the thermal conductivity unit can be calibrated. A decade resistance box is connected to pins C and D of the input plug of the thermal conductivity unit. The

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range switch on the unit is set to the 0° to 10°C range and the display mode switch is set to T. The decade resistor box is set to the equivalent resistance of the thermistor at 5°C. Referring to Fig. 12, the output of IC9 (pin 6) and the wiper of R114 are grounded while R111 is varied so that the panel meter reads 0.000 V. The ground is removed from the wiper of R114 and this resistor is adjusted so that the meter reads 5.000 V. Next the wipers of switches S10C and S10D are grounded. R108 is adjusted to bring the meter reading back to 5.000. The grounds are then removed from the switch wipers. R73 is then adjusted so that the meter reads 5.000. The decade resistance box is changed to the resistance for 0°C and R54 adjusted so that the meter reads 0.000 V. The resistance box is returned to the 5° setting and R73 readjusted if necessary. Repeat the procedure until no further adjustment is necessary to the two controls. Set the range switch to the 10° to 20° range and set the decade resistor to a resistance equal to the 15°C value for the thermistor. Set R72 for a meter reading of 5.000 V. Set the decade resistance to the 10°C value and adjust R55 for 0.000 V on the meter. Repeat these steps for all the temperature ranges of the unit, first setting the decade resistance box to a resistance equivalent to the center of the range, and then to the bottom of the range. After the initial adjustment, R108, R111, and R114 need not be readjusted.

ACKNOWLEDGMENTS

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